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Experiments on a Miniature Hypervelocity Shock Tube

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Abstract. A miniature explosively-driven shock tube, based on the Voitenko compressor design[1], has been designed with a goal of producing shock speeds in light gases in excess of 80 km/s. Voitenko compressors over 1 meter in diameter have been reported[2] but here experiments on a shock tube with a ~1-mm bore diameter are presented. In this design a 12.7 mm diameter explosive pellet drives a metal plate into a hemispherical gas compression chamber. Downstream from the piston a mica diaphragm separates the gas from an evacuated shock tube, which is confined by a massive polymethylmethacrylate (PMMA) block. The diaphragm eventually ruptures under the applied pressure loading and the compressed gases escape into the evacuated shock tube at hyper velocities.

The progress of gas shocks in the tube and oblique shocks in the PMMA are monitored with an ultra-high-speed imaging system, the Shock Wave Image Framing Technique (SWIFT).[3] The resulting time-resolved images yield two-dimensional visualizations of shock geometry and progression. By measuring both the luminous gas front and oblique shocks, accurate and unequivocal measurements of shock position history are obtained. The experimental results were compared with those of hydro-code modelling to understand the salient features of the apparatus and optimize the design. The first experiments were suboptimum in that the velocities were ~16 km/s. Progress with these experiments will be reported.

1. Introduction

Methods of accelerating particles to high velocity and their impacts with solid targets have long been of interest to various communities including shock physics, high energy density physics and space travel. Recently a new avenue of interest is the impact of nanoparticles (1 to 10 nm in diameter) at velocities approaching 100 km/s. These particles undergo shock compression to stresses of ~10 TPa in times of the order of 10 fs to 100 fs. Bae[4, 5] demonstrated experimentally that as these particles relax they emit soft X-rays with high efficiency.

Bae proposed that under such conditions, because electron-ion thermalization takes longer than 1 ps, thermalization is minimized and the initial compression energy is mainly mechanical, i.e., the compression is 'cold'. Under these unique conditions the nanoparticles are compressed into the metastable inner-shell molecular state (MIMS), which is bound by inner-shell electrons with binding energies exceeding 100 eV. It is the decay of the MIMS state that is accompanied by X-ray emission.

In Bae's experiments low-density fluxes of nanoparticles were accelerated electrically. To study the physics of hypervelocity short duration impact with larger fluxes, we propose to accelerate nanoparticles using a combination of explosive and electrical techniques. A miniature explosively driven shock tube has been designed and tested which is similar to the Voitenko compressor design[1], with the exception of scale. Voitenko compressors over 1 meter in diameter have been previously reported[2], more typically compressors have meter scale tube lengths. Here experiments on miniature shock tubes with ~1-mm bore diameters ~30 mm in length are described. High precision photographic techniques are employed to examine the shock progression in detail with nanosecond resolution.

2. Instrumentation

SWIFT[3] is a versatile, inline, lens-based, ultra-high-speed imaging system capable of Schlieren, shadowgraph, and backlight recording of explosive experiments with minor hardware adjustments. In SWIFT, a SIMD (Specialised Imaging) camera records shock wave positions, which are backlit by a Reveal 5 (Spectra-Physics) 5 Watt CW 532 nm Laser, with a 5 ns exposure time and frame rate as short as 5 ns but typically 150 to 200 ns. A polished PMMA block was used to mechanically support the experiment and associated gas/vacuum fittings. During the execution of the experiment the PMMA effectively becomes a shock wave transducer for SWIFT. During shot setup and alignment, a scale image is taken with a calibrated target (Edmund Ind. Optics, P/N 57-985). Analysis of the scale image determines the conversion factors in X and Y (μm/pixel) enabling precise measurements of shock positions.

3. Miniature Compressor Design

The mechanical design of the miniature hyper-velocity shock tube is shown in Figure 1. It consisted of a two-piece PMMA housing with the upper block housing the high explosive (HE) pellet and the lower block housing the shock tube. PBX-9407 (94% RDX with 6% Exon 461 binder, ϱ_0 = 1.65 g/cm^3) pressed in a 12.7 mm right cylindrical pellet was used as the HE drive. An alignment ring was used to axially center the detonator to ensure detonation symmetry. The piston consisted of a 0.127 mm thick, 12.75 mm diameter 302 stainless steel plate that was mounted under the HE pellet and held in place with quick setting epoxy. A brass insert was used to retain a 25.4 μm thick Mica membrane. The mica membrane formed the boundary between the explosively driven gas chamber, which contained air at STP, in the upper block and the evacuated shock tube housed in the lower block. The lower tube had a diameter of 0.64 mm with a length of 27.31 mm and was held at ~40 mbar for each experiment.

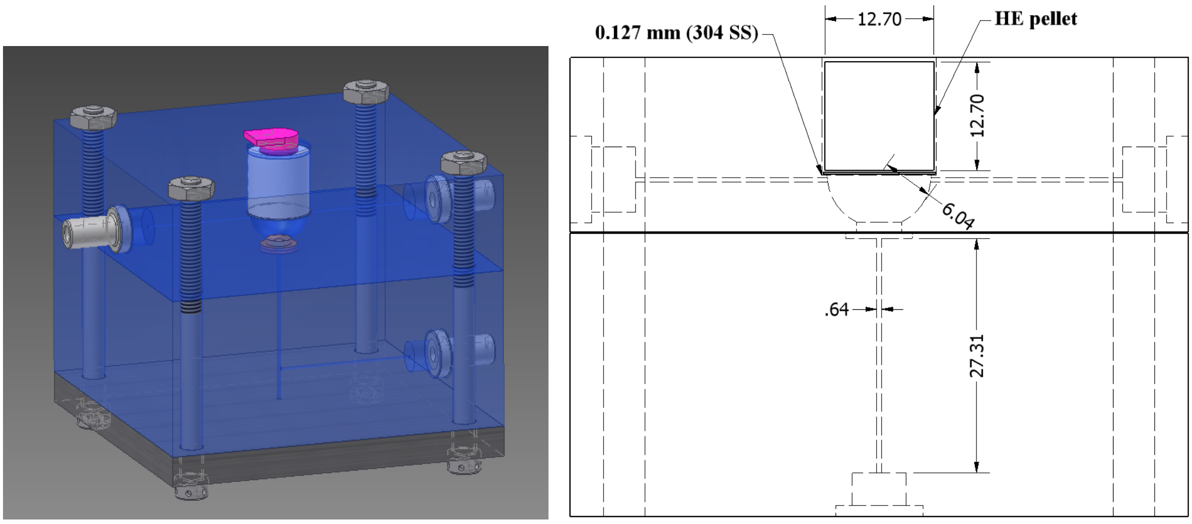

Figure 1. The miniature Voitenko compressor design is shown here with mechanical dimensions in mm. Gas fittings are included to allow gas flow in the hemispherical bowl as well as vacuum access for the lower tube.

4. Results and Discussion

The operation of the miniature Voitenko compressor begins with detonator operation followed by HE initiation and detonation. The HE drives the piston downward into the bowl shaped cavity, which rapidly compresses the gas therein. Shortly before the piston reaches the bottom of the bowl, either due to differential pressure, radiant heating, or a combination of the two, the mica membrane ruptures/vaporizes. The highly compressed gas then violently decompresses into the evacuated shock tube at high velocity. The key parameters affecting the velocity of the jet are gas density and pressure, shock tube diameter, shock tube initial pressure, bowl shape, rupture diaphragm material and thickness, and HE performance properties (P_{CJ} and D) and detonation wave shape.

The SWIFT diagnostic used in this work recorded the stress waves from the HE pellet, gas motion in the bowl, and gas jet propagation in the shock tube as shown in Figure 2. Image frames in Figure 2 are numbered 1 through 16 from top to bottom and left to right. Frames 1 – 4 show the detonation of the PBX-9407 pellet. The compression of the hemispherical bowl is recorded in frames 5 – 10. A 1.125 μs delay was inserted between frame 10 and frame 11 to compensate for the diaphragm rupture time. Frames 11 – 16 record the plasma jet being driven into the evacuated tube at high velocity.

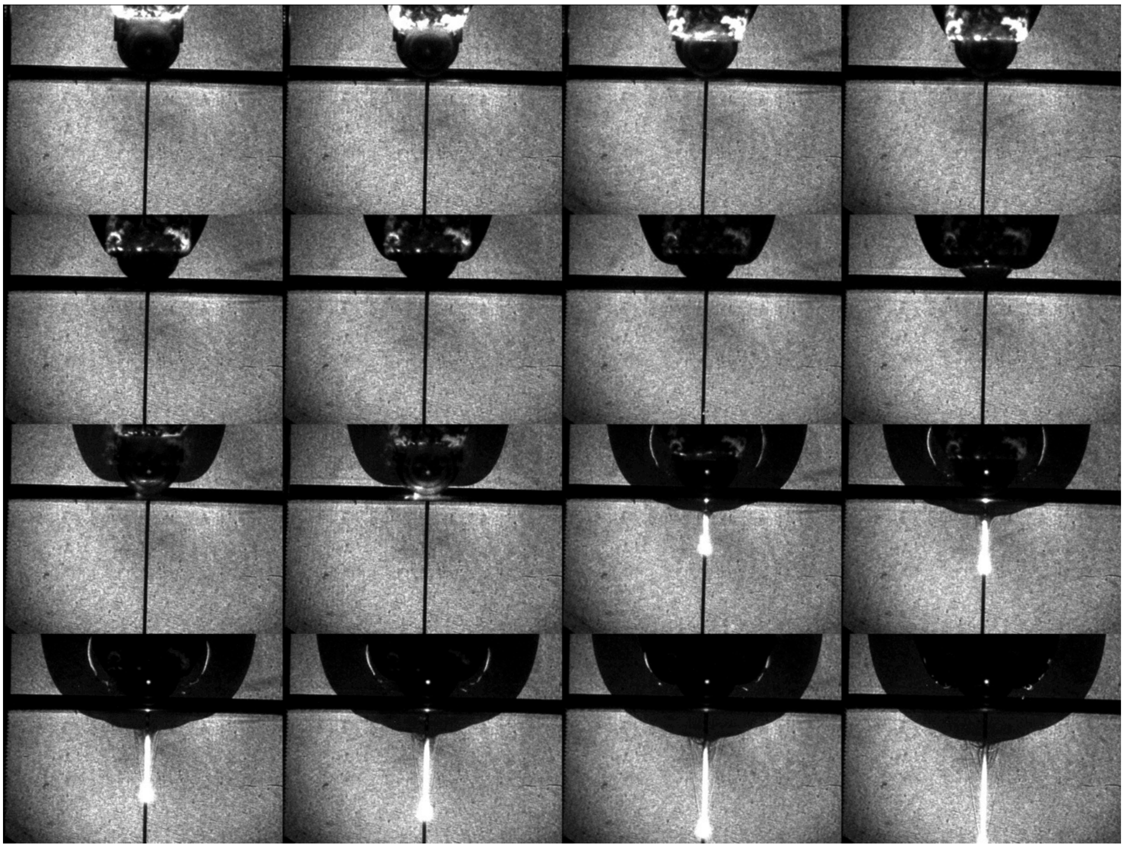

Figure 2. The SWIFT images of the miniature Voitenko compressor operation capture three stages of compressor function: detonation, compression, and jet propagation. Exposure time is 5 ns with inter-frame timing of 225 ns; a 1.125 μs delay was inserted between frames 10 and 11.

The SIMD CCD pixels were saturated due to the extreme temperature and brightness of the jet in the last several frames. To determine jet velocity the pixel saturation boundary was taken from frames 11 – 15, frame 16 was not used since the jet had left the field of view. A linear least-squares fit to the data, see Figure 3, shows that jet velocity is 15.99 +/- 0.54 km/s. From Figure 3 we can also infer that, at least during the ~1 μs period of observation, jet velocity is constant. Additional analysis of stress waves propagating from the shock tube, just visible in frames 11 – 15, lead to a similar jet velocity result. Hydro-code calculations were completed with ALE3D and an average jet velocity of ~ 10 km/s was obtained. It is expected that the Eulerian mesh treatment used introduced some error due to the advection of mass through the mesh.

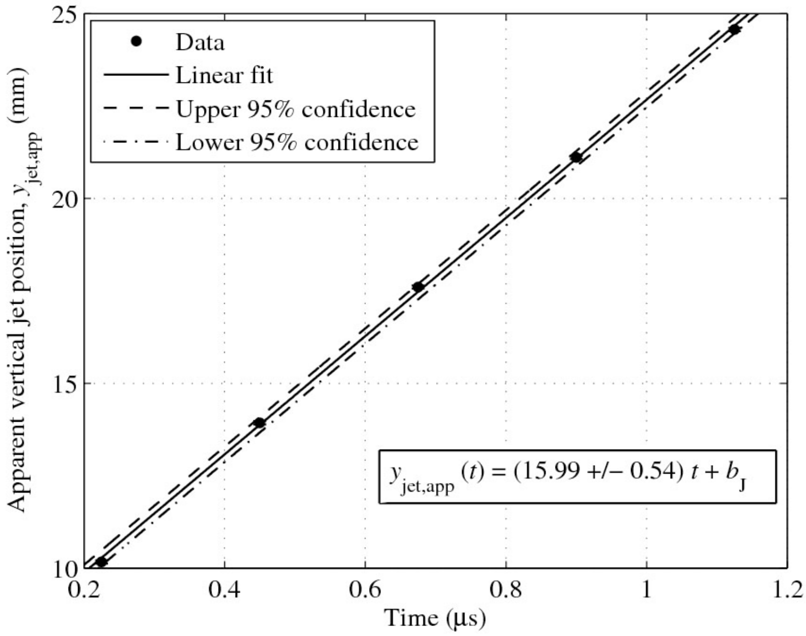

Figure 3. The jet position, taken as the saturation boundary, from frames 11 – 15 is plotted along with a linear least-squares fit to the data. The analysis reveals a jet velocity of 15.99 +/- 0.54 km/s.

5. Conclusions

A miniaturized Voitenko compressor driven by a 12.7 mm right cylindrical pellet of PBX-9407 was observed to generate a jet velocity of 15.99 +/- 0.54 km/s in a 0.635 mm diameter tube. The SWIFT diagnostic has shown that the luminous plasma jet front surface is collocated with the leading edge of a radially expanding conical shock wave. The quality of SWIFT data provides an unambiguous interpretation of jet position in several image frames and is a powerful tool in the development and understanding of hypervelocity phenomena. Modifications to the design and additional experiments are underway to increase jet velocity to the desired ~80 km/s range.

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